Instrumentation challenges for e^+e^- colliders

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e^+e^- Machines on the horizon

- ILC
  - Technical Design Report 2013
    Volumes I-IV
- CLIC
  - Conceptual Design Report 2011/12
    Vol I, II, III
- TLEP
  - TLEP: A High-Performance Circular e+e- Collid
    er to Study the Higgs Boson
    4th International Particle Accelerator Conference (IPAC 2013)

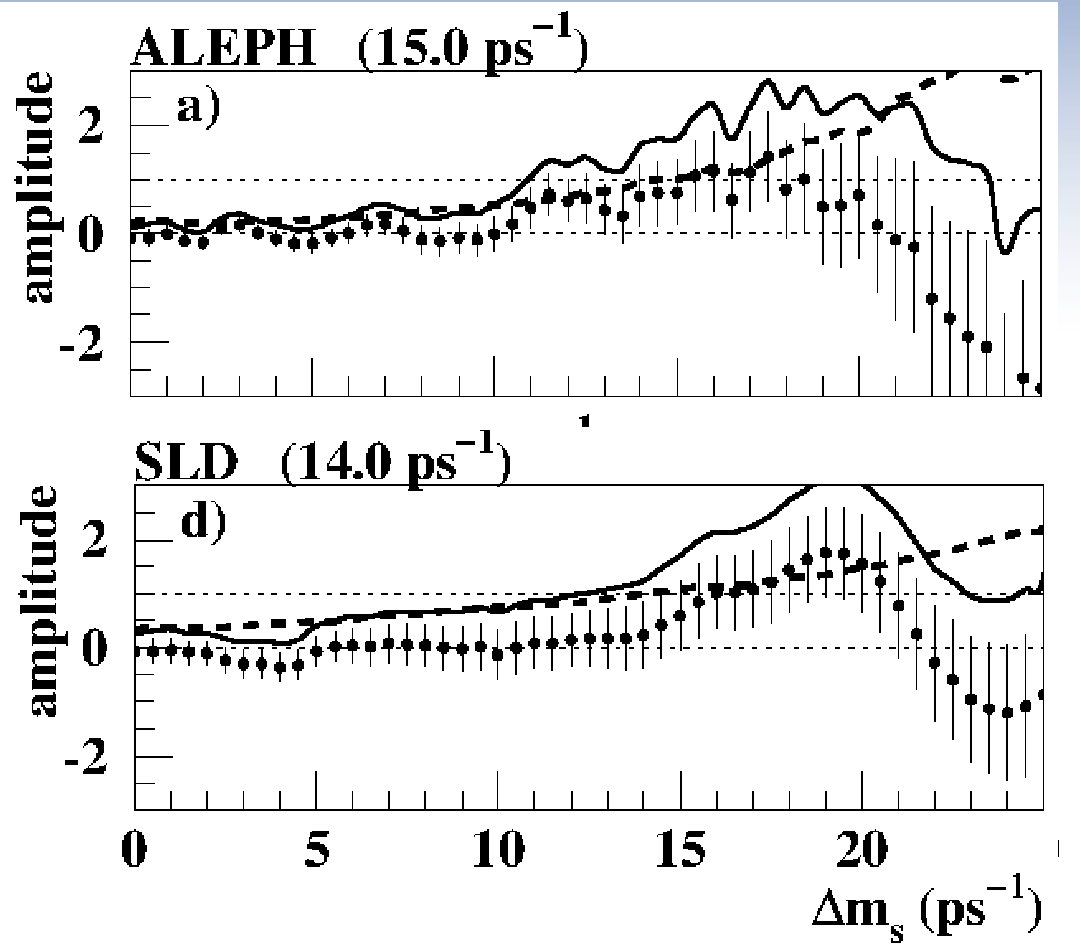
Machine Parameters

	ILC	CLIC	TLEP
$\sqrt{s}$ (GeV)	(91/) 250-1000	350 -3000	91-350
Min Bunch spacing (ns)	366	0.5	
Bunches/Train	2625	312	4400
Collision Rate (Hz)	5	50	
Luminosity (10^{34})	4.9	5.9	56
Number of pairs/BX	~4 x 10^5	~7x10^8	?
$\gamma\gamma \rightarrow$ hadrons/BX	4.1	3.6	?

This is always taking the most challenging parameter set ...

It is not just the luminosity

- Bs Oscillations
- ALEPH (LEP)
    - ~ 6 million Z's
- SLD
    - ~ 300000 Z's
- Main advantage of SLD:
    - Pixel Vertex detector
    - Much closer to the IP



Timescales

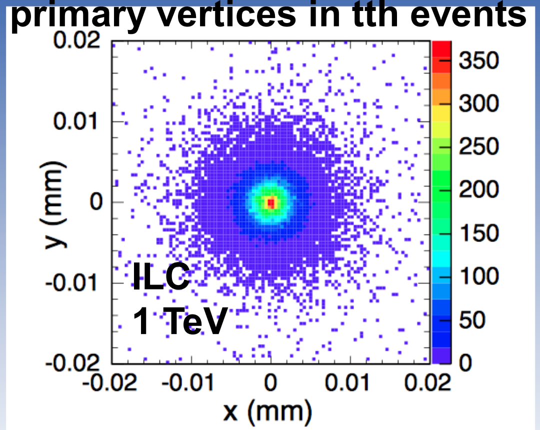
- This is my personal forecast ...
    - Everyone is entitled to its own crystal sphere
- HL-LHC
    - Start of data taking 2022/3
- ILC
    - Start of data taking 2027/8
- CLIC/TLEP
    - After the end of the HL-LHC program (2030+)
    - ~2035

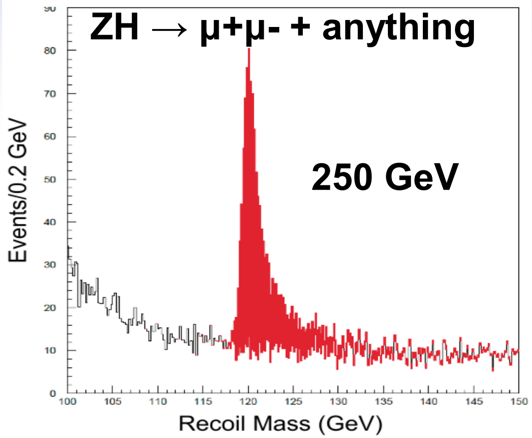
Detector requirements

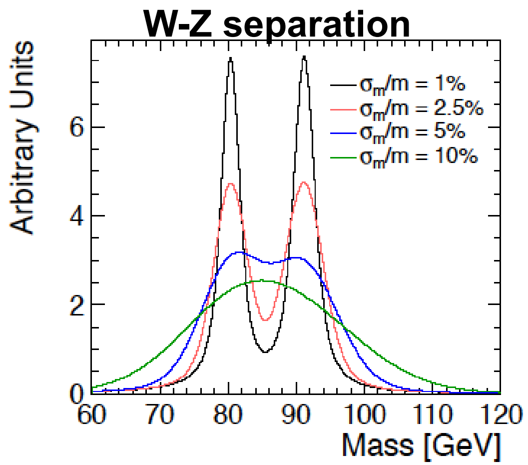
- All Lepton machines require
  - Highly granular, low-mass detectors
  - Radiation hardness is mostly not an issue
  - Full angular coverage,
  - Minimizing dead regions & materials
  - Single bunch time resolution
  - Robustness against machine backgrounds

Sub-Detector Requirements

- Exceptional precision & time stamping
  - Single Bunch resolution
- Vertex detector
  - < 4 μm precision
  - $\sigma_{r\varphi} \approx 5\ \mu m \oplus 10\ \mu m / p \sin^{\left(\frac{3}{2}\right)}(\theta)$
- Tracker
  - $\sigma(1/p) \sim 2.5 \times 10^{-5}$
- Calorimeter
  - $\frac{\sigma_{E_{Jet}}}{E_{Jet}} = 3-4\%, E_{Jet} = 50-500\ \ GeV$





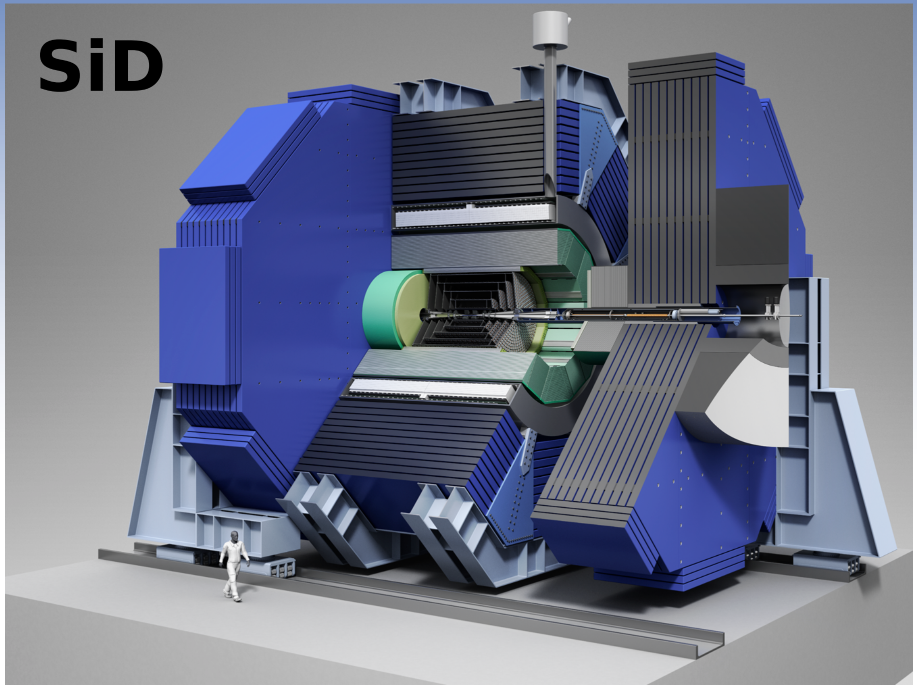


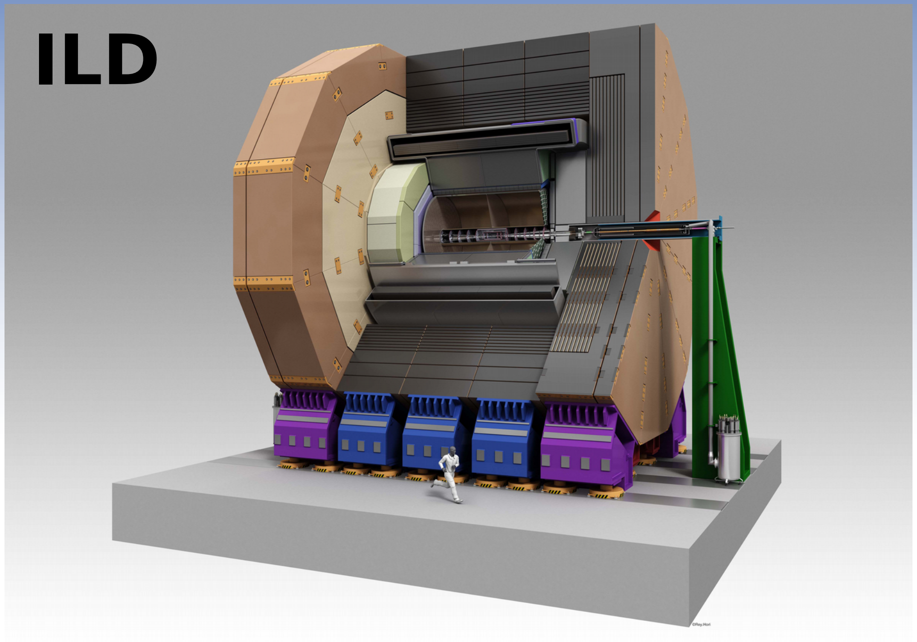
Different challenges

- Calorimeter granularity
  - Need factor ~200 better than LHC
- Pixel size
  - Need factor ~20 smaller than LHC
- Material budget, central tracking
  - Need factor ~10 less than LHC
- Material budget, forward tracking
  - Need factor ~ >100 less than LHC

Requirements for Timing, Data rate and Radiation hardness are very modest compared to LHC

Proposed detectors for the ILC





- Both SiD and ILC built with Particle Flow in mind
  - Drives the entire design
- CLIC uses variants (CLIC_SiD, CLIC_ILD) adapted for 3 TeV operations
- TLEP so far used CMS for simulations

Detector R&D status

- SiD and ILD designs have been extensively reviewed by external experts
  - International detector advisory group (ILC)
  - CDR Review group (CLIC)
- For many systems, SiD and ILD are clearly beyond “proof-of-principle”
  - Documented in the Detailed Baseline Designs of the ILC TDR
  - Exception is the Vertex detector, this is an open issue
- SiD and ILD have “Baseline Designs”
  - Remain open for new ideas

Main R&D issues

- Focus is moving towards System issues
  - Powering schemes
  - Cooling & Thermal management
  - Mechanics & Material budget
  - Interconnects
  - DAQ
- Nanosecond-Timestamping remains important R&D goal for CLIC

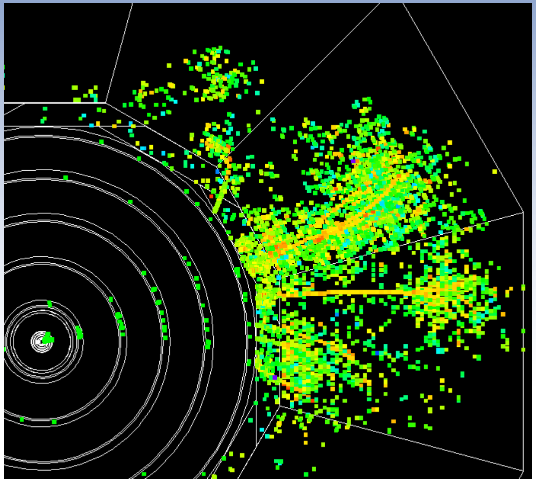
Vertex Detector

- Neither concept has selected a baseline
    - No technology is just there yet
- Requirements
    - <20 x 20 µm pixels, time stamping, ultra-thin, low-power
- Many ideas on the market
    - Monolithic Active Pixel sensors (MAPS)
    - DEPFET
    - Fine-pitch CCD's
    - 3D Pixels
    - Hybrid pixels (mainly for CLIC)

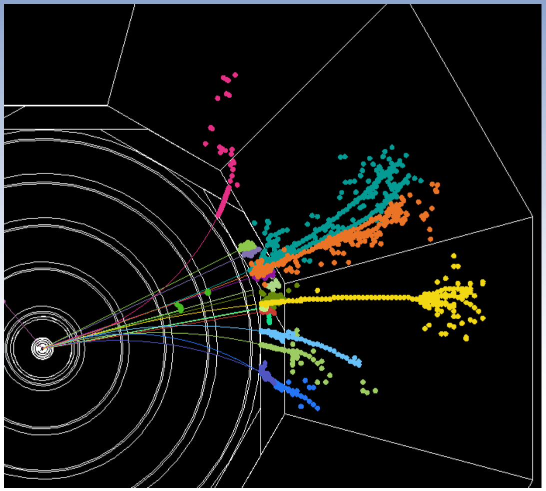
Vertexing for CLIC

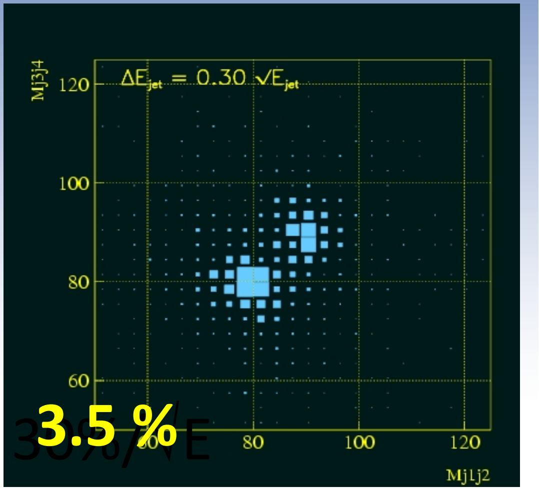
- CLIC environment makes the Vertex Detector a tad more challenging
  - 0.5 ns time stamping
  - Machine backgrounds for Multi-TeV runs
- 3-4μm point resolution,
- 10 ns/√12) time resolution,
- $<0.2\%X_0$ per layer implying
  - low-power design,
  - power pulsing
  - gas cooling

PFA calorimetry



PFA

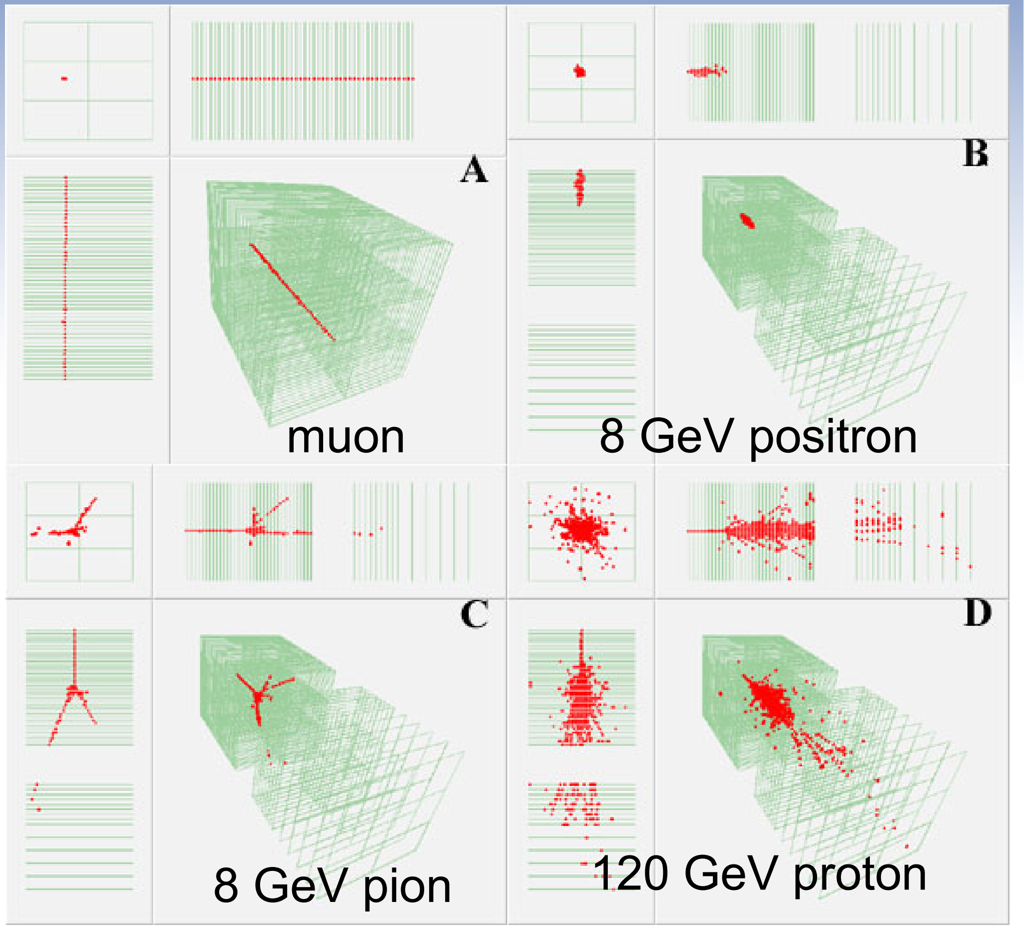




- Implementing a successful PFA system is both a hardware and a software challenge
- Requires an integrated approach to detector design: tracking ⊕ calorimetry
- Intense R&D Effort the last ten years

PFA HCAL

- RPC-based Digital HCAL
  - Lead by ANL
- 1 m^3 Stack
  - 1x 1 cm^2 cell size
  - 500000 channels
- Scintillator-based analog HCAL
  - Lead by DESY
- Proof of principle made
- PFA successfully applied to test beam data

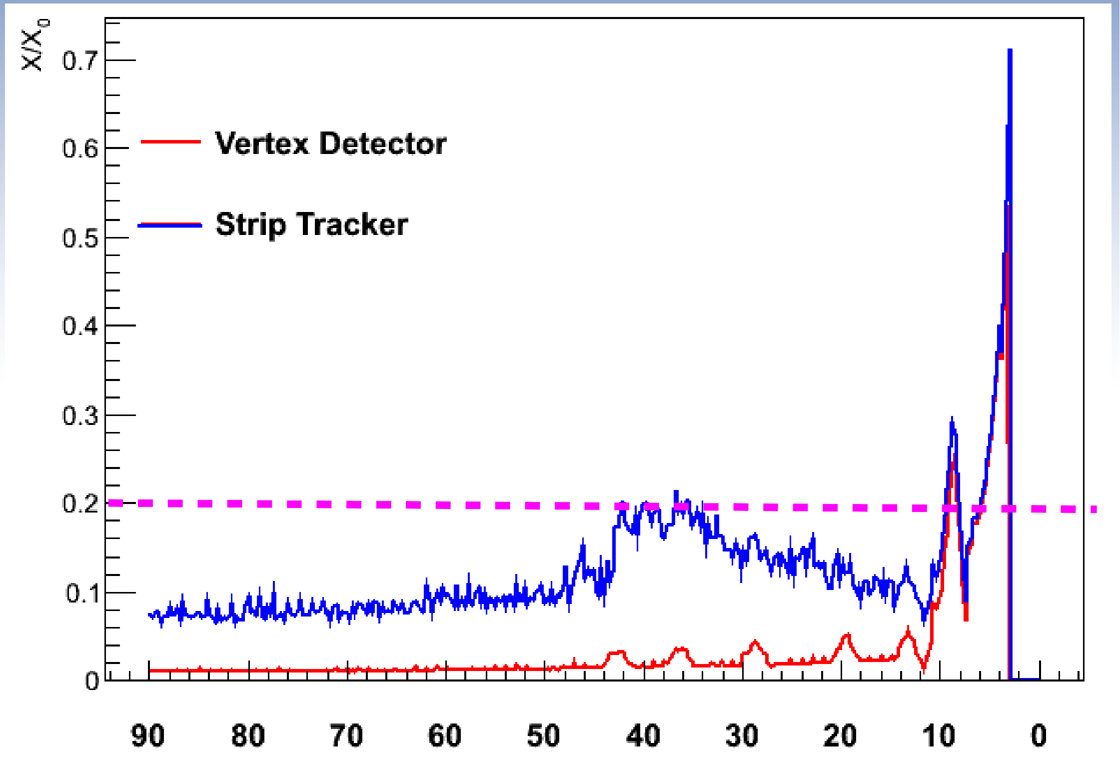


Power Pulsing

- A key component of all ILC/CLIC detectors
  - Using duty cycles e.g. ILC case
    - 199 ms quiet
    - 1 ms live
  - Powering down “front-end during quiet- time
  - Factor O(100) power saving
- Proof-of-principle straightforward
- System-level studies have only started
  - Need to understand impact of pulsing millions of channels ..

Material budget

- Goal
  - 20 % X/X_0
- Required
  - Lightweight rigid structures
  - Gas cooling
  - Eliminating hybrids
  - Power conversion (DC-DC)
- Can we use new lightweight materials ?



The Challenging questions

- Energy Frontier → Instrumentation Frontier
  - In some studies for ILC and CLIC, the sophistication of particle flow calorimetry approaches the ability to resolve single hadrons. At what point does the evolution of particle flow calorimetry give a qualitative, rather than just a quantitative, boost to experimental capabilities? Can we realistically reach this point?
  - In the context of proposals of large tunnels that could host both pp and e+e- colliders, it is interesting to ask whether it is possible to design 4 pi detectors that can be used both for pp and e+e- experiments (perhaps with some interchangable inner tracking layers). Is there an optimal design of such a multi-purpose detector? What are the most important compromises required?
- Instrumentation Frontier → Energy Frontier
  - how important is fast time stamping of the signals from the detector? For which detector parts would this be most important calorimeter? tracker?
  - how important is the forward region, how far in η do we need to cover?
  - how important is high b-tagging efficiency at low pT/at high pT?, what can we do with better Vtx resolution

Re-using detectors

- Hadron collider
  - Fast BX (25 ns)
  - Radiation hard
  - Fancy trigger system
- Lepton collider
  - Relaxed BX
  - Radiation soft
  - No/simple trigger

- Tracker/Vertexing need to be exchanged for sure
- Calorimetry may be also …
- Differences in Timing and trigger will require significant exchange of electronics …
- Power & cooling needs will be different

Taking this into account

- The Breidenbach Model
- Steel and Solenoid can be re-used
  - About 150 Mio $ savings
- Everything inside will be exchanged
  - e^+e^- Slide-In
  - Hadron Slide-In
- This is probably the most sensible way to do
  - Price of two optimized detectors ~1000 Mio US-$
  - Slide-In approach ~ 850 Mio US-$
- In any way, you'll end up with a non-optimal detector for either case

Additional improvements for PFA

- Established the 3.5% Goal for ILC physics
  - Do we need to better ?
  - Do we gain further capabilities?
- Considered
  - W/Z separation, see next slide
  - Hadronic resonances will benefit from better resolution
  - Event-based reconstruction (e.g π^0 reconstruction)
  - Particle-ID inside jets

W/Z separation

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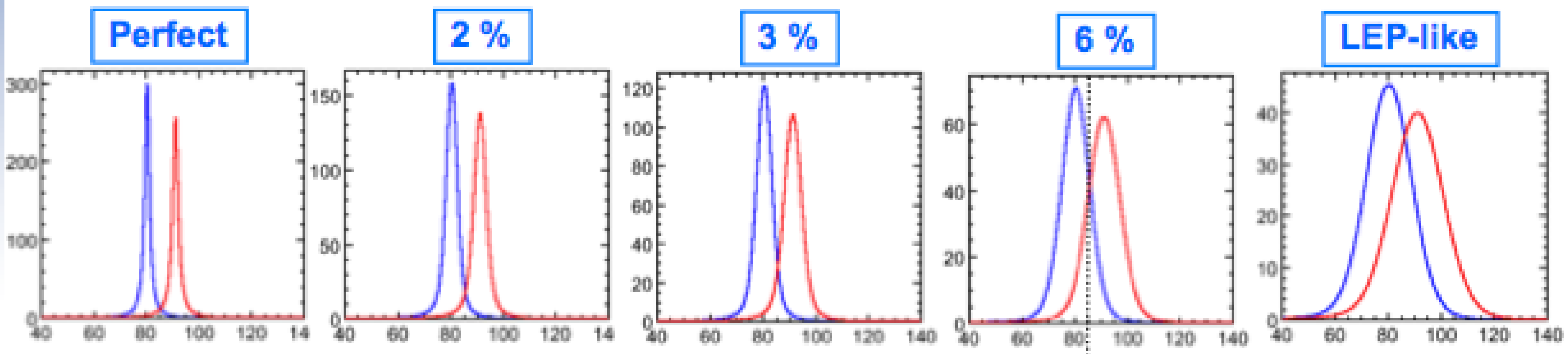
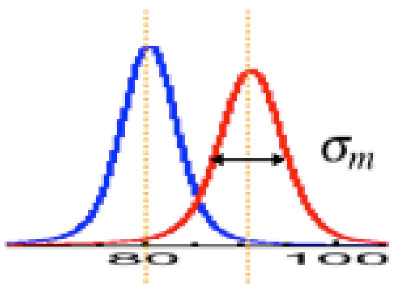
- Gauge boson width sets "natural" goal for **minimum** jet energy resolution



- Quantify by **effective** W/Z separation

$$\mathrm{W/Z\ sep} = (m_Z - m_W)/\sigma_m$$

Jet E res.	W/Z sep
perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ



Defined as **effective** Gaussian equivalent Mass resolution

- 3 – 4 % jet energy resolution give decent W/Z separation 2.6 – 2.3 σ
- sets a **reasonable** choice for Lepton Collider jet energy **minimal goal ~3.5 %**
- for W/Z separation, not much to gain beyond this as limited by W/Z widths

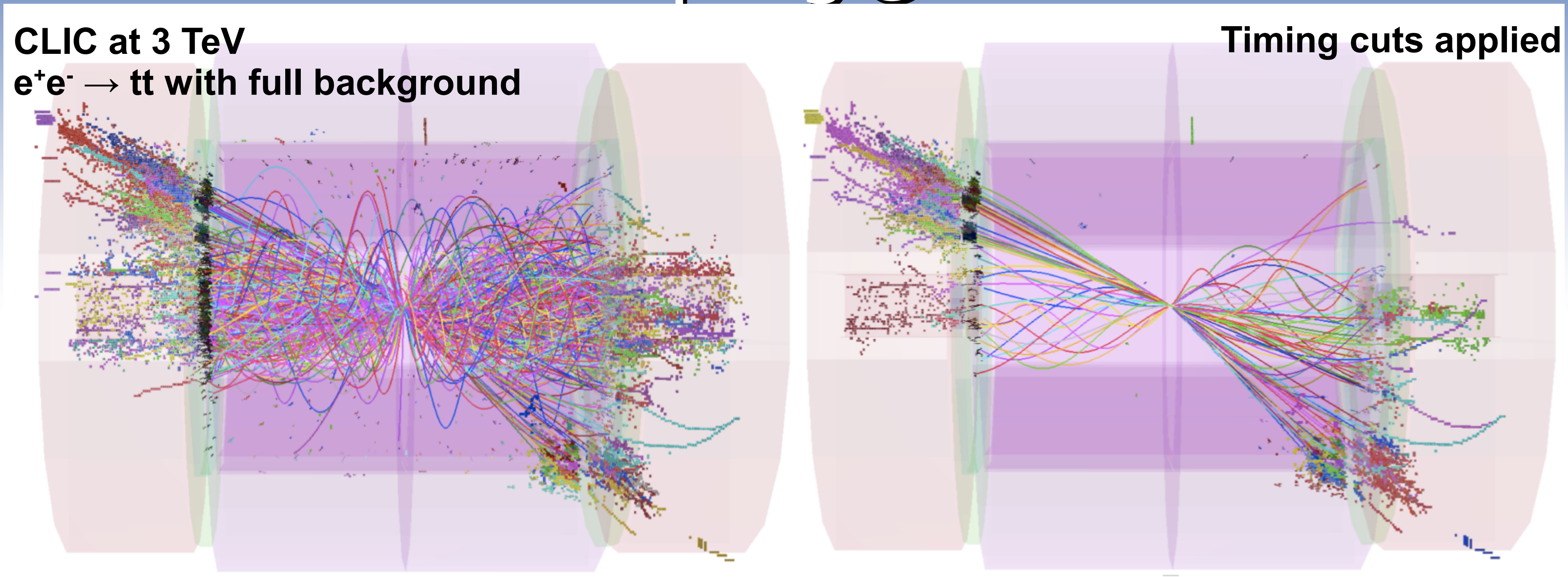
PFA conclusions

- Reaching the 3 % Jet Energy resolution
  - Game-changing
- Go significantly below
  - We of course gain
  - Lot's of things one could do to take advantage of this
- Ultimately, going from 3 to 1 % won't have the same impact
  - Unless some new physics demands this

What can we do with ps timestamping

- Nanosecond time stamping is really needed at CLIC
- Beyond nanosecond level
  - Difficult to see a real need right now
- Potential ideas
  - Particle ID
  - Timing for PFA reconstruction
- Balance these with the power budget

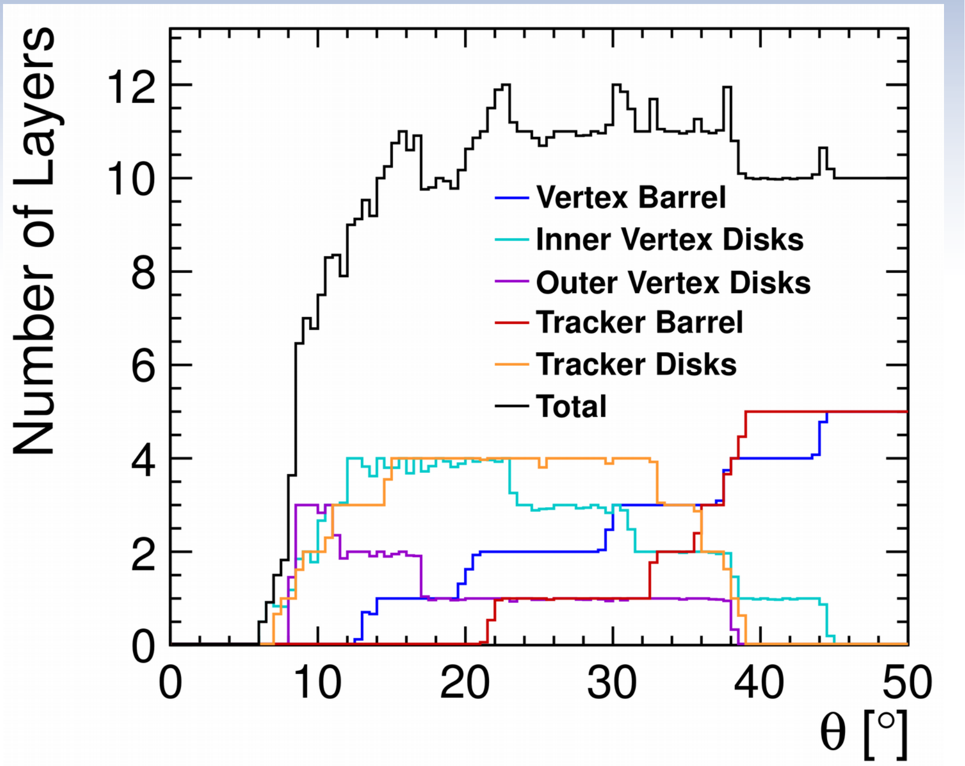
Nanosecond Time Stamping@CLIC



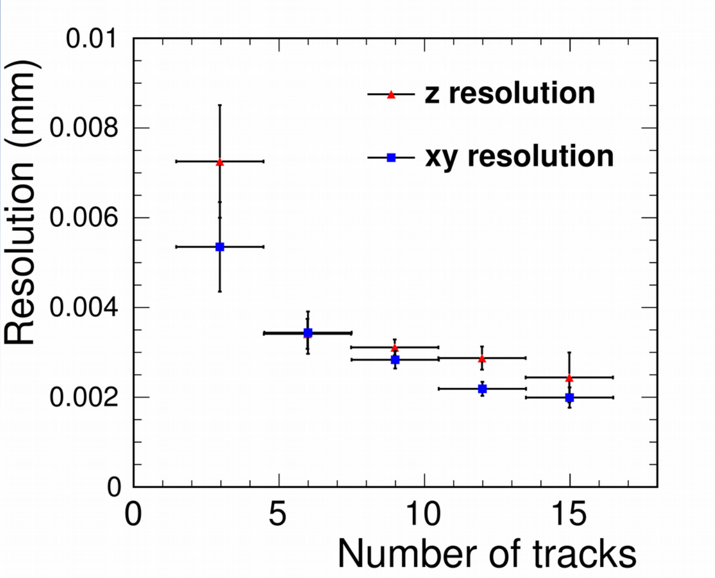
- Timing cuts rely on precise time stamping
  - >10 ns in the tracker
  - 1 ns in the calorimeter

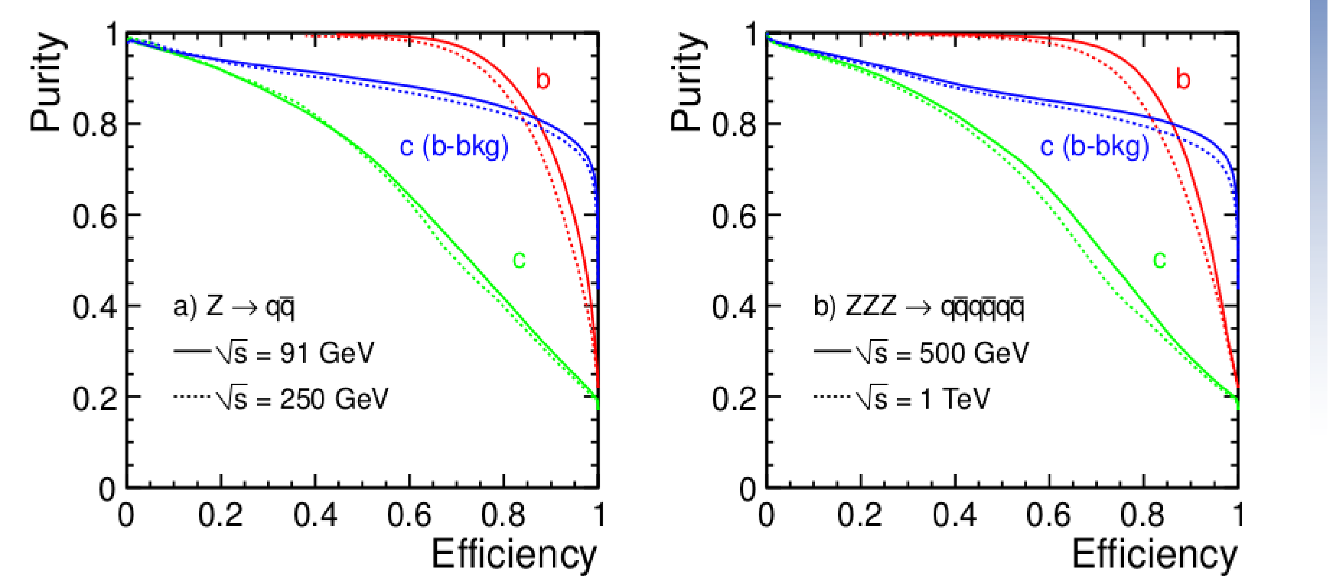
η Coverage

- e^+e^- does not deal in η
- Forward coverage is important
  - t-channel processes at higher energy
- Detectors
  - Full tracking down to 8 degrees
- Can always do better
  - Limited by final focus system
  - Backgrounds



Vertexing resolution





- Present Vertexing resolution already impressive
  - Very performant flavor tag
- What would a factor of ten bring ?
  - Increased c-tagging performance
  - B-tagging is already very performant
- Limited by e.g. beampipe radius

Conclusions

- For ILC/CLIC Detectors, start looking at system issues
  - Years of intense R&D effort worldwide
- Vertex Detector technology
  - Not quite there yet , active area of R&D
- Thanks to
  - Jim Brau, Marty Breidenbach, Norman Graf, Ulrich Heintz, Lucie Linssen, Felix Sefkow, Mark Thomson, Andy White, Graham Wilson for discussion and material